# Chapter 6: Directional Antenna Systems

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# MANET Throughput

- **All MAC and routing protocols assume omni-directional transmission**
- **It fundamentally limits how high one can push the capacity of the system**
- **A thorough study of the capacity of the ad hoc system is performed shows that the throughput obtainable by each node is:**

$$\Theta\left(\frac{W}{\sqrt{n \log n}}\right)$$

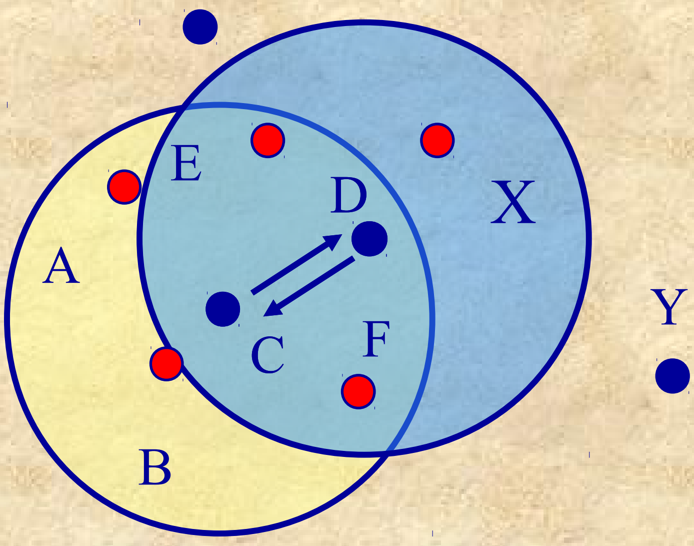
  **where *W* is the data rate and *n* is the number of nodes in the network**
- **This limitation on capacity exists irrespective of the routing protocol or channel access mechanism**
- **Directional antenna systems are a powerful way of increasing the capacity, connectivity, and covertness of MANETs**

# Advantages of Directional Antennas

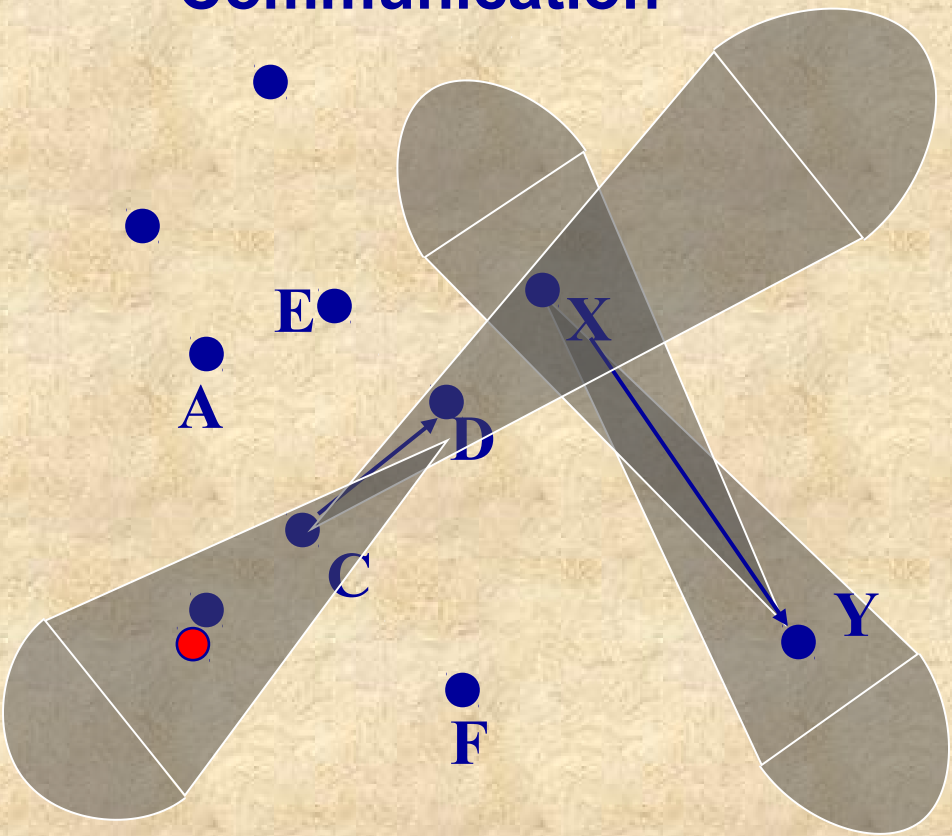
- Directional antennas can focus electromagnetic energy in one direction and enhance coverage range for a given power level
- They also minimize co-channel interference and reduce noise level in a contention-based access scheme, thereby reducing the collision probability
- Further, they provide longer range and/or more stable links due to increased signal strength and reduced multipath components
- Increased spatial reuse and longer ranges translate into higher network capacity and longer ranges also provide richer connectivity
- On the receiving side, directional antennas enable a node to selectively receive signals only from a certain desired direction

# Omni/Directional Communication

**Omni-directional Communication**




**Directional Communication**



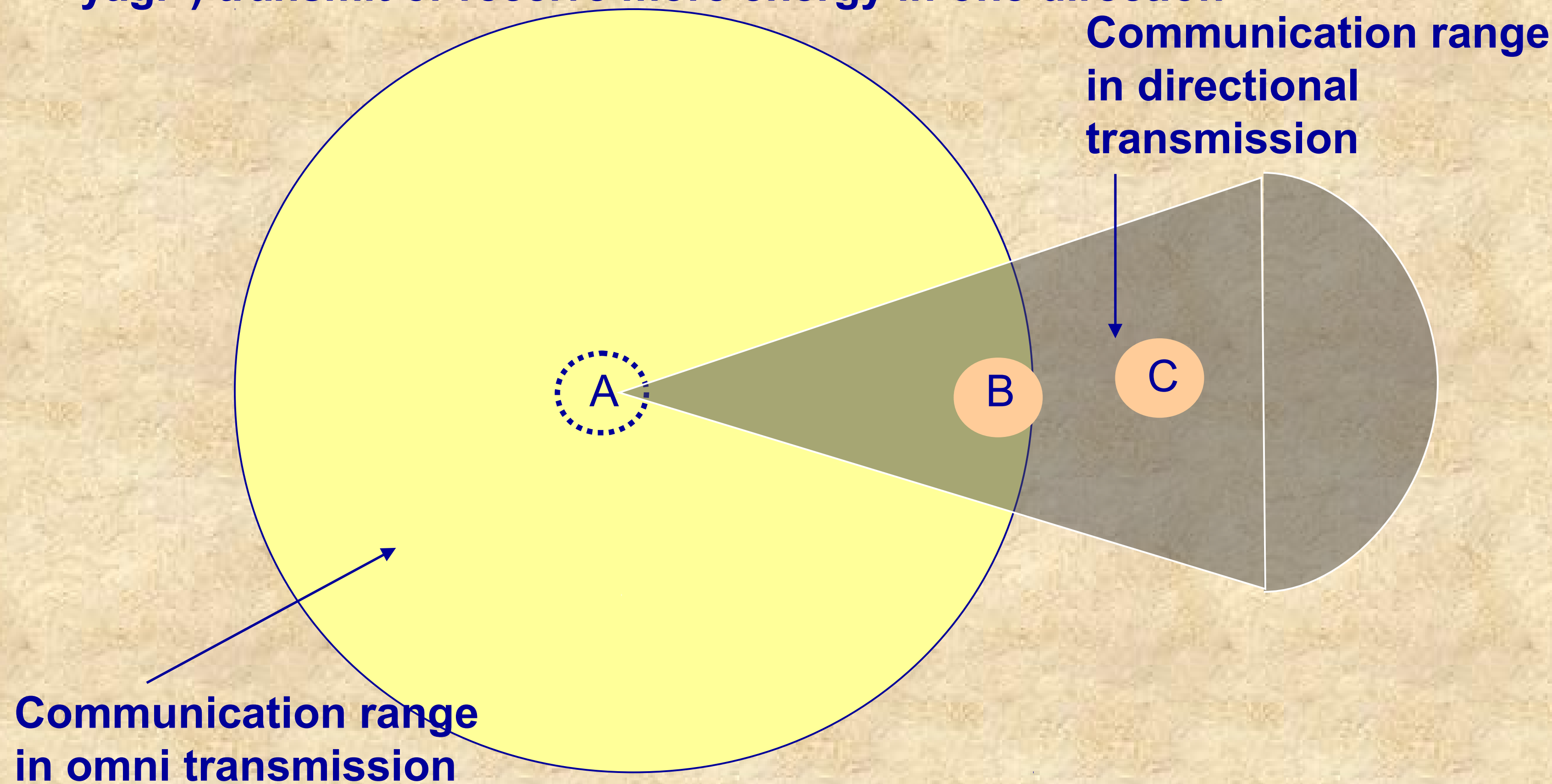

**Red nodes Cannot Communicate presently**

# Comparison of Omni and Directional antennas

| Characteristics | Omni | Directional |
| --- | --- | --- |
| Spatial reuse | Low | High |
| Network connectivity | Low | High |
| Interference | Omni | Directional |
| Coverage range | Low | High |
| Cost and complexity | Low | High |

# Coverage Range of Omni-directional and Directional Transmissions

- Simple dipole antenna whose length depends on the wavelength λ and radiation pattern is supposed to be symmetric in all directions
- On the other hand, more focused directional antennas (also called "yagi") transmit or receive more energy in one direction



# Antenna Gain

- Antenna with a “higher” gain does not amplify the signal more than another with “less” gain
- An antenna with greater gain simply focuses the energy of the signal differently
- Omni antennas radiate transmit power in all directions and listen for incoming messages from all directions
- Yagi (directional) antennas focus their radiated transmit power in one direction and also listen for incoming signals with a more focused ear
- Yagi antennas, therefore, tend to send a signal farther than omni antennas with the same gain
- For a given direction, the gain of the directional antenna is given by where $G(\vec{d})$ gives the power density in direction d

$$G(\vec{d}) = \eta \frac{U(\vec{d})}{U_{avg}}$$

$U_{avg}$ is the average power density over all directions, $\eta$ is the efficiency of the antenna which accounts for losses and $U(\vec{d})$ is power density in direction

- Gain is generally measured of decibels (dBi), where $G_{dBi} = 10\log10\ (G_{abs})$

# Characteristics

***Radiation Pattern***

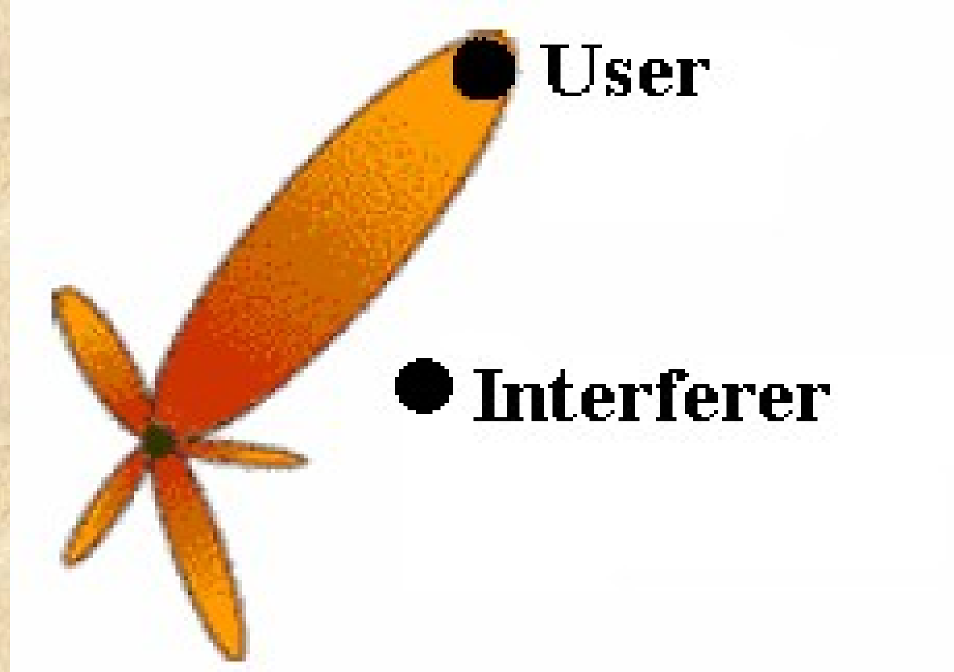
- **Radiation or antenna pattern describes the relative strength of the radiated field in various directions from the antenna, at a fixed or constant distance**
- **It generally has a main lobe of peak gain and side lobes**
- **Peak gain is the maximum gain taken over all directions**
- **Beam is also used as a synonym for “lobe”**
- **A related concept in the antenna system is beam width**
- **A “half power beam width” refers the angular separation between the half power points on the antenna radiation pattern, where the gain is one half of the peak gain**

***Beam Width***

- **A common definition is the half power beam width: -3dB**
- **Evolution of Directional Antenna Systems**
  - **Sectorized Antenna Systems**
  - **Diversity Antenna Systems: Switched Diversity and Diversity Combining**
  - **Smart Antenna Systems: Switched beam antenna systems and Adaptive antenna arrays**

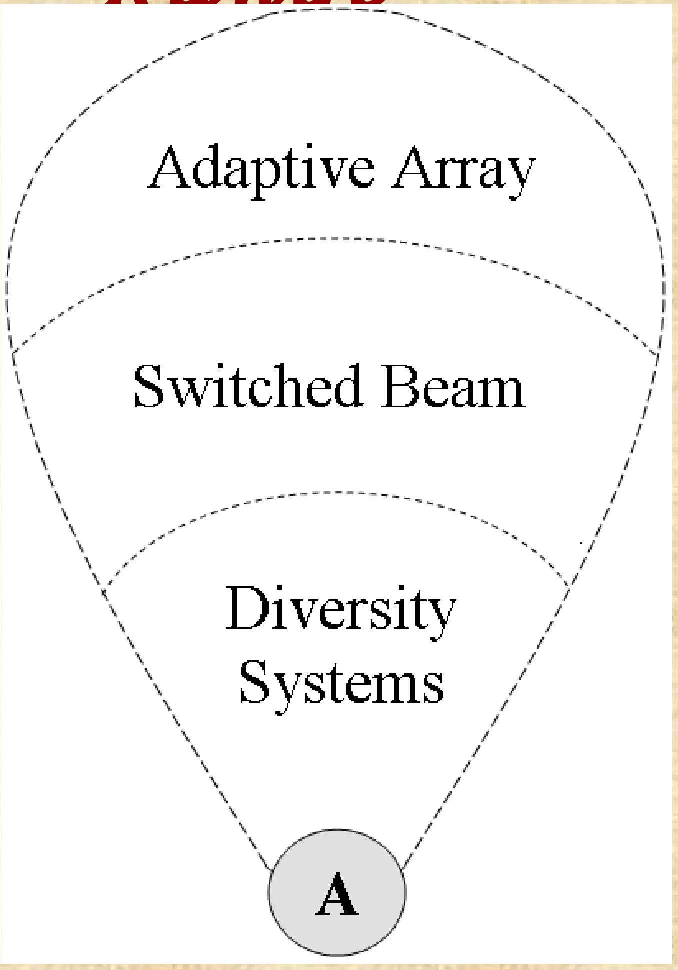
# Comparison of switched beam and adaptive array antenna systems

(a) – Switched beam



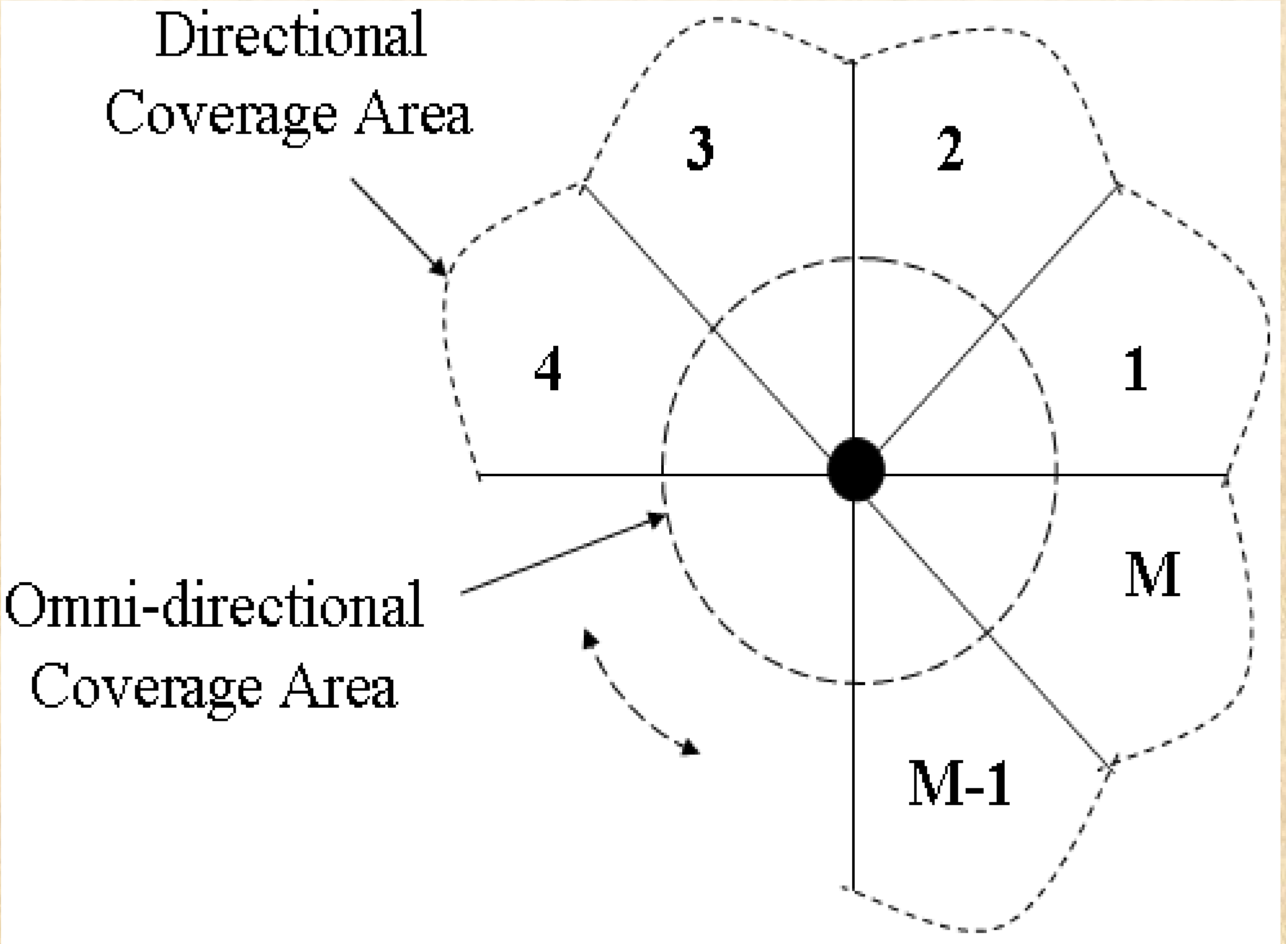

(b) – Adaptive array

# Directional Antenna Coverage Range




- Interference rejection capability provides significantly more coverage than either the sectorized or switched beam systems
- The use of multiple antennas at both ends of a communication link provides a significant improvement in link reliability, spectral efficiency (MIMO)
- Using multiple antennas at both ends enables multiplexing of data streams
- Since each of the independent antenna beams requires independent digital signal processing controllers, increases the cost

# Omni/Directional Coverage



# Advantages of Using Directional Antennas

- **Antenna with a "higher" gain does not amplify the signal more than another with "less" gain**
- **Antenna Gain:**
  - **Entire transmission energy directed towards a particular direction to increase the transmission range**
- **Array Gain:**
  - **Multiple antennas can coherently combine the signal energy, improving the SNR both ends**
- **Diversity Gain:**
  - **Spatial diversity from multiple antennas can help to combat channel fading**
- **Interference Suppression:**
  - **Adaptively combine multiple antennas to selectively cancel or avoid interference**
- **Angle Reuse:**
  - **Reuse frequency at angles covered by different antenna beams (SDMA) and can support more than one user in the same frequency channel**
- **Spatial Multiplexing:**
  - **Multiple antenna beams at both ends of the wireless link dramatically increase the bit rates**

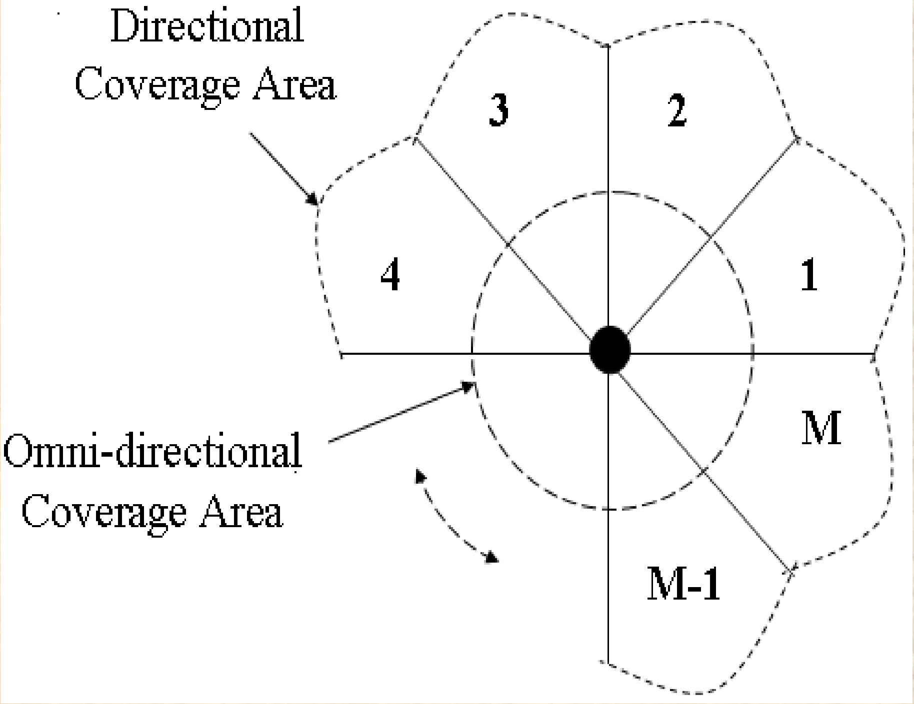
# Directional Antennas for Ad Hoc Networks

- Future applications will demand different types of antenna systems so as to meet requirements such as cost, size, energy constraints, performance, …..
- Main applications of ad hoc networks can be classified into different categories
  - Military: The nodes (tank, airplanes) are expensive and the cost of even the most sophisticated antenna may be acceptable while beamforming antennas can provide a better immunity to jammers
  - Outdoor or disaster recovery: A switched antenna steerable beam can be used to reach different nodes (too expensive) and for small handheld devices, laptops and PDAs, the size of the antenna may be a complicating factor
  - Indoor applications

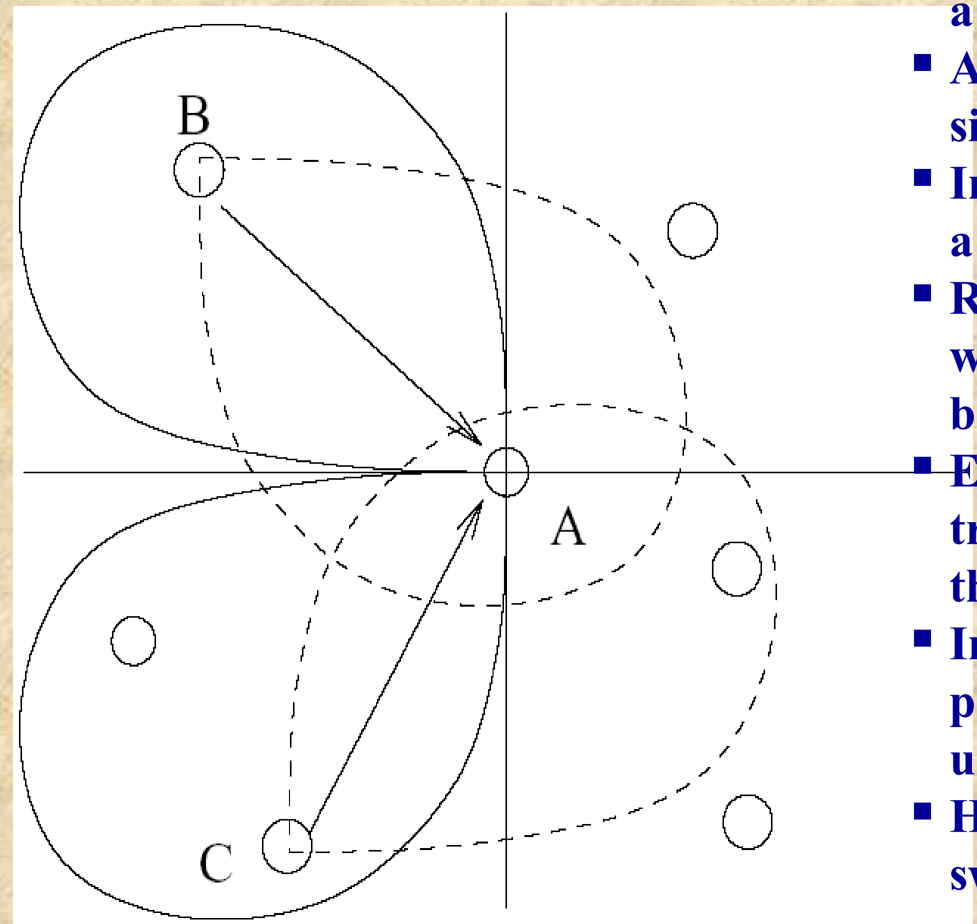
- *Antenna Models*
  - Antenna type need to define medium access control scheme to address hidden and exposed terminal problems
  - Routing protocols need to take into account issues such as the particular direction a node can be found: New neighbor discovery mechanisms and availability of multiple paths
  - Two antenna models: The switched beam antenna model and the adaptive antenna arrays model

# Switched Beam Antenna Model

- Two separate modes: Omni and Directional
- In *Omni* mode, a node is capable of receiving signals from all directions with a gain of $G^o$
- While idle (i.e., neither transmitting nor receiving), a node usually stays in *Omni* mode
- In *Directional* mode, a node can point its beam towards a specified direction with gain $G^d$ (with $G^d$ typically greater than $G^o$), using an array of antennas called array of beams
- Due to higher gain, nodes in *Directional* mode have a greater range in comparison to *Omni* mode

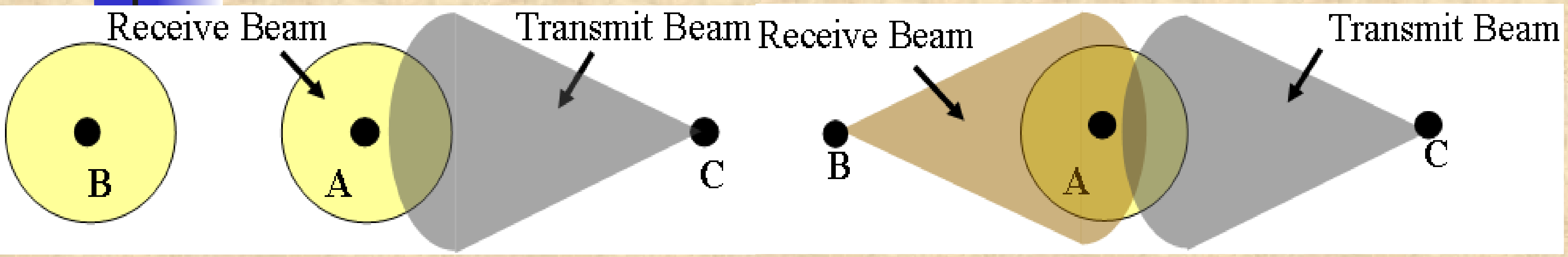


# Adaptive Antenna Array Model




- Switched beam antenna model allows only a single transmission or reception
- Adaptive antenna array allows multiple simultaneous receptions or transmissions
- In adaptive antenna arrays, each beam has a beam width of approximately $\pi/2$ radians
- Receiving beams are shown by solid lines while transmitting beams are shown using broken lines
- Even though the areas covered by the transmit beams of nodes B and C overlap, they do not cause collision at node A
- Interference may be caused when a particular beam has side lobes in undesirable directions
- However, most research assumes perfect switched beams sidelobes

# Protocol Issues on the Use of Directional Antennas




**Nodes A and C are directional-omni (DO) neighbors**

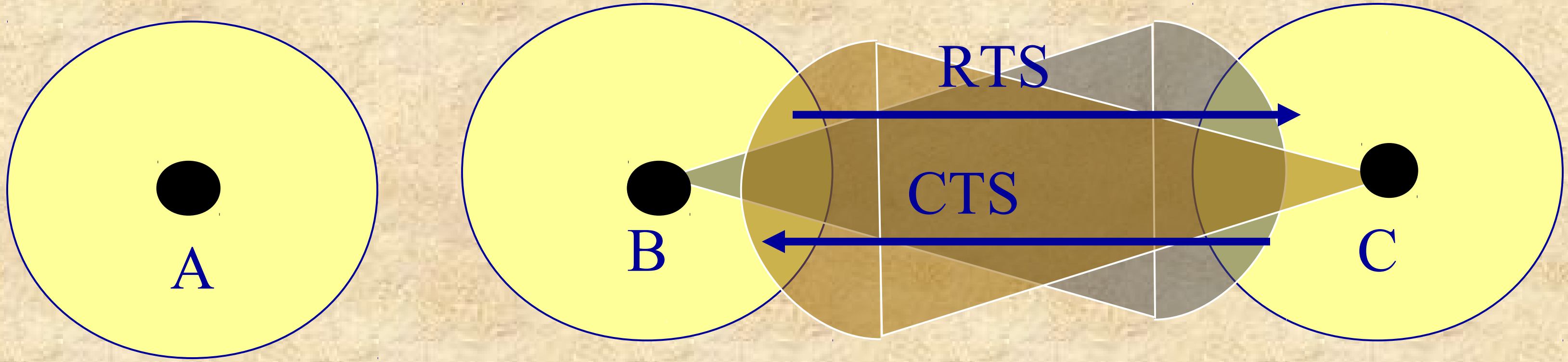
**Nodes B and C are directional-directional (DD) neighbors**

- **Directional Neighborhood**
  - **To perform a complete "broadcast", a node may have to transmit in a circular manner as many times as the antenna beams sweeping**
  - **Such a scheme emulates a broadcast as performed by omni-directional antenna**
  - **However this is not so simple, as delay is associated with the sweeping procedure**
  - **As the number of beams increases, so is the sweeping delay**

# New Types of Hidden Terminal Problems

Two types of Hidden Terminal Problems

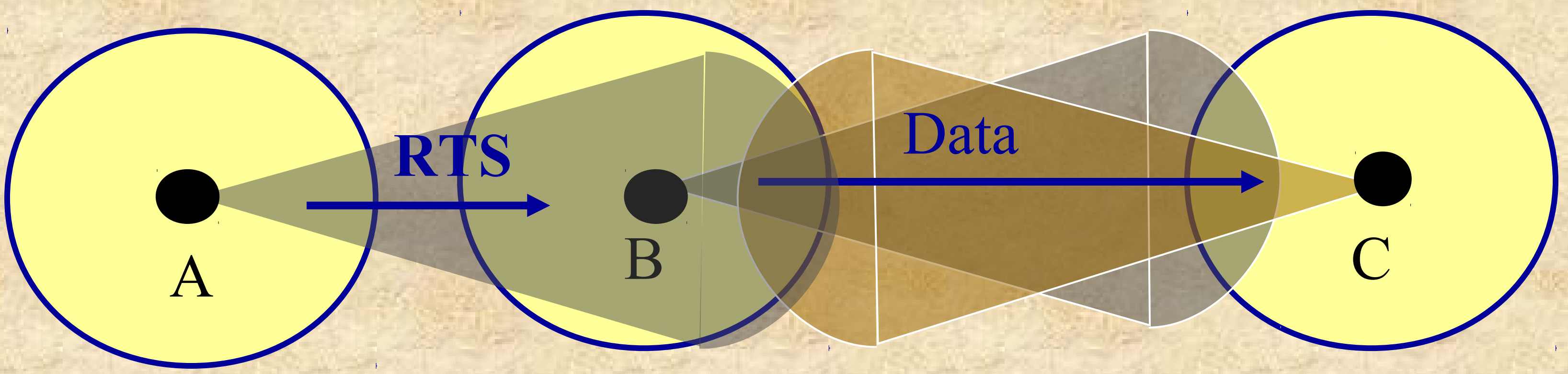
Due to asymmetry in gain




A is unaware of communication between B and C

# New Types of Hidden Terminal Problems

- Two types of Hidden Terminal Problems
  - Due to asymmetry in gain

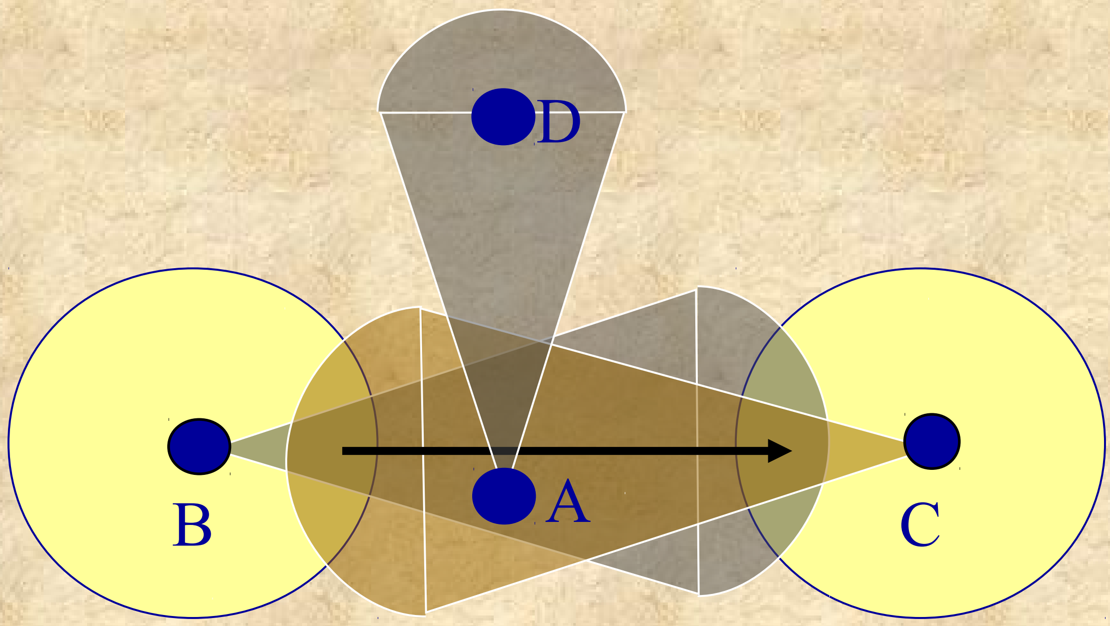



A's RTS may interfere with C's reception of DATA

# Unheard RTS/CTS

Two types of Hidden Terminal Problems

Due to unheard RTS/CTS

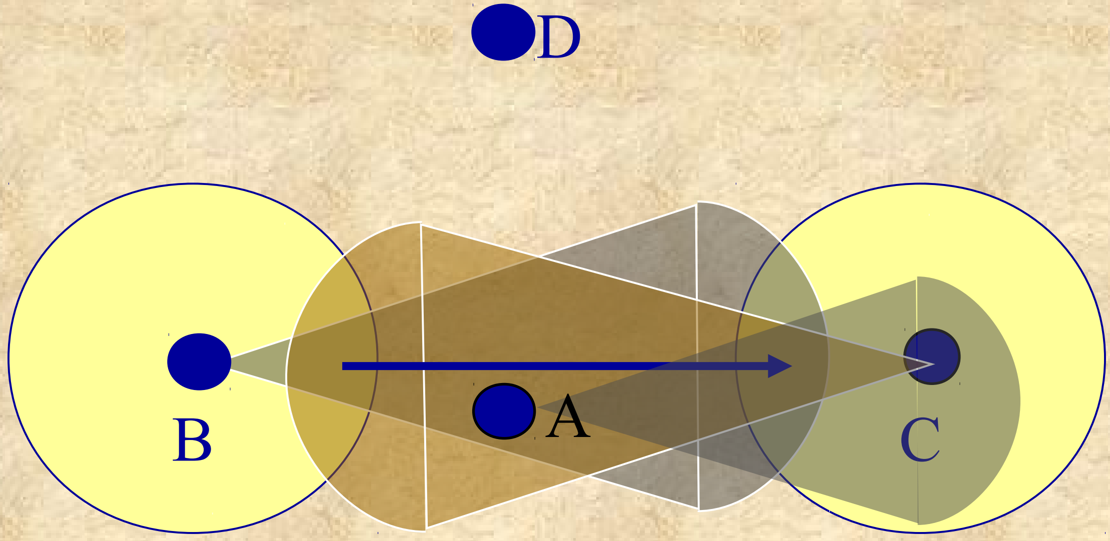



- Node A beamformed in direction of D
- Node A does not hear RTS/CTS from B & C

# Unheard RTS/CTS

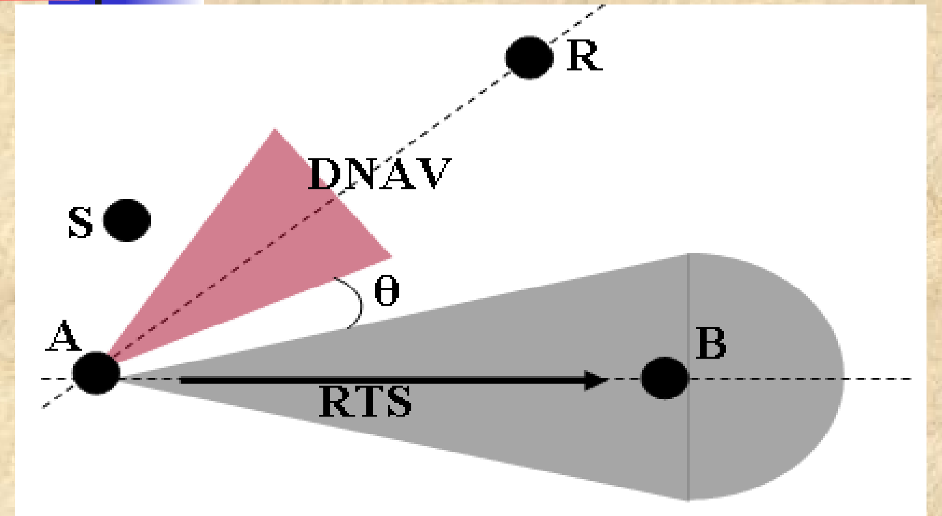
Two types of Hidden Terminal Problems

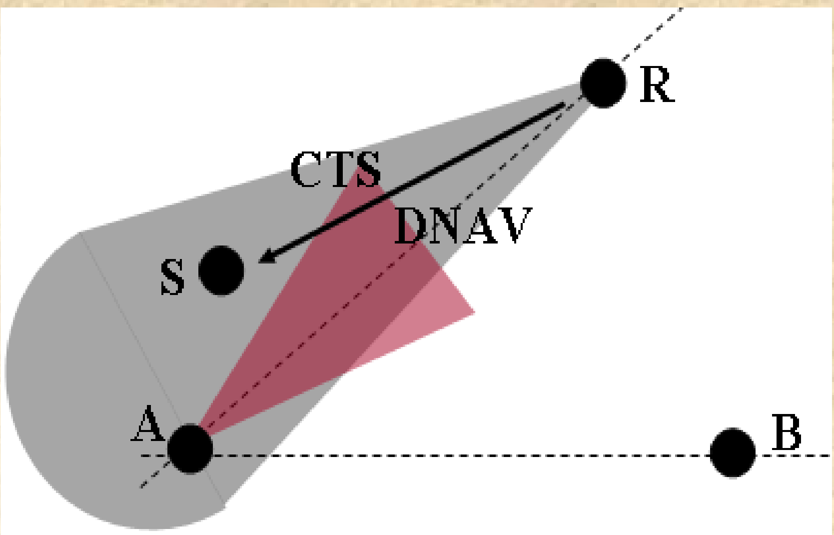
Due to unheard RTS/CTS




Node A may now interfere at node **C** by transmitting in C's direction

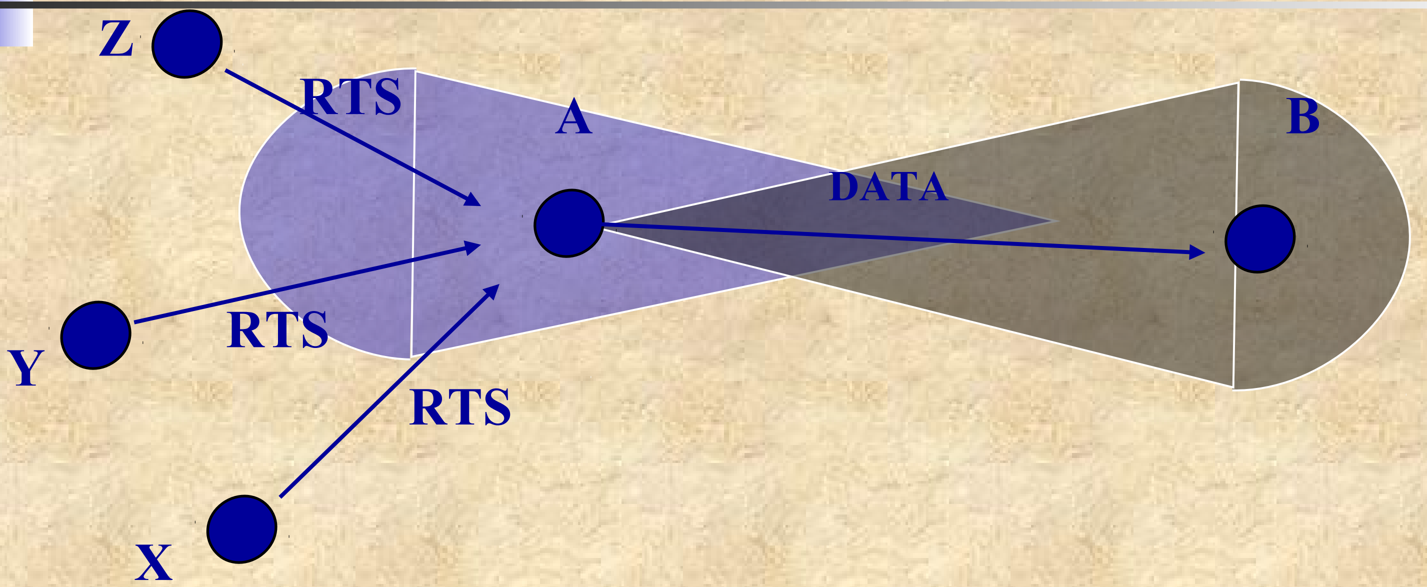
# The Directional NAV (DNAV)



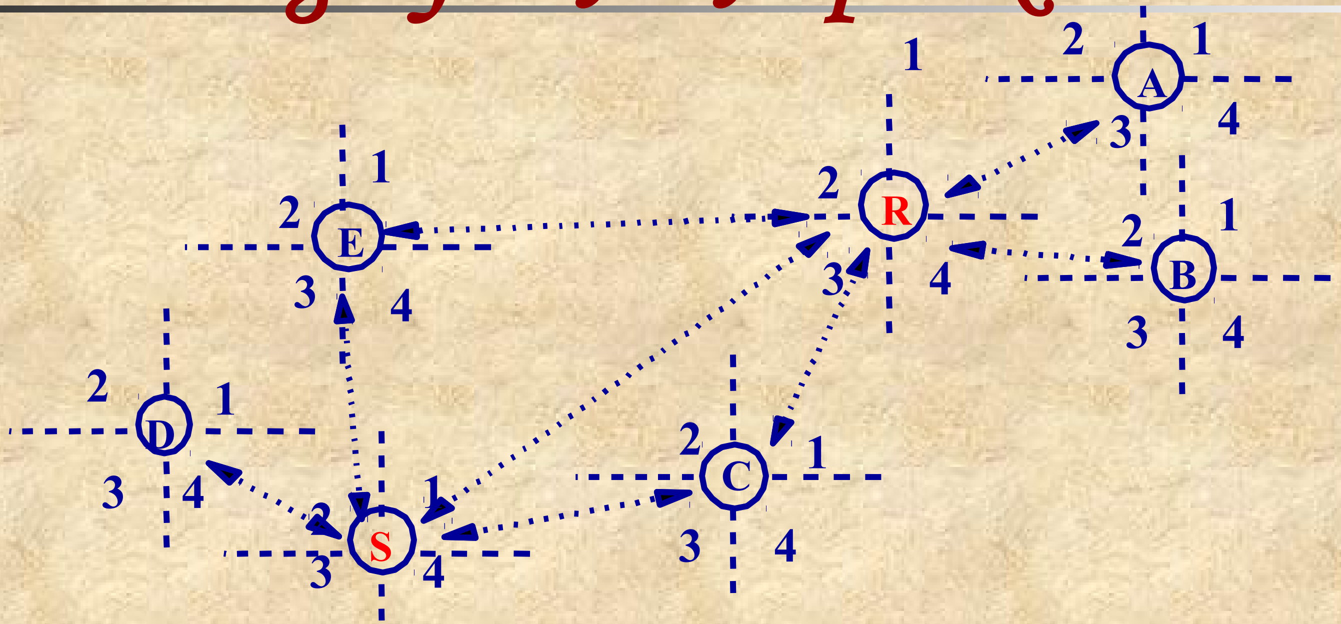

- Directional NAV (DNAV) is an extension to the NAV concept used in IEEE 802.11
- DNAV is a table that keeps track for each direction of the time during which a node must not initiate a transmission
- Nodes continuously update the DNAV table upon overhearing a packet transmission
- Node S sends an RTS to node R which in turn sends back CTS
- Nodes overhearing either the RTS or the CTS set their DNAV in the Direction of Arrival (DoA)
- This will prevent node A from initiating any transmission towards node R
- Node A is allowed to transmit to node B

# Deafness




- Deafness is defined as the phenomenon when a node X is unable to communicate with a neighbor node A, as A is presently tuned to some other directional antenna beam
- Unless node A informs all its neighbors in advance about its communication with node B, its neighbors might unsuccessfully try to contact it
- X does not know node A is busy, X keeps transmitting RTSs to node A
- Using omni antennas, X would be aware that A is busy, and defer its own transmission

# Deafness due to the persistent hearing of DATA packets




- It does not suffice to stay silent in the direction through which a packet has been received
- Persistent hearing of DATA packets may occur in almost all MAC protocols proposed for directional antennas, with four antennas beams per node
- When a node sends RTS/CTS (either directional or omni), all neighbors who receive it set their NAV (or DNAV) accordingly
- Whenever the source node starts transmitting the DATA packet, neighboring idle nodes overhear this DATA transmission and change to directional mode, hence becoming deaf to all other directions
- A data communication is to be carried out between nodes S and R
- Clearly, node C will detect the forthcoming data communication due to the RTS/CTS handshake between S and R
- As a consequence, node C will move to directional mode towards node S whenever the DATA transmission originating at node S starts
- Therefore, if in the meantime node F tries to send an RTS to C (received through beam 4), node C will not reply as it is currently beamformed in the direction of node S's DATA transmission

# Broadcasting

- Routing protocols including DSR, AODV, ZRP, LAR, etc. use variants of a network-wide broadcasting to establish and maintain routes
- Protocols use simple flooding for broadcasting
- Simple flooding causes redundancy and increases the level of contention and collisions in a network
- With directional transmission, both transmission range and spatial reuse can have nodes concentrate energy only towards their destination's direction
- A simple solution to broadcasting is to sequentially sweep across all the pre-defined beams of the antenna system
- Broadcast by sweeping incurs a sweeping delay
- Efficient schemes need to be designed to take the antenna system characteristics into consideration in reducing redundancy and sweeping delay

# Adaptive Antenna Array Based Broadcasting Protocols

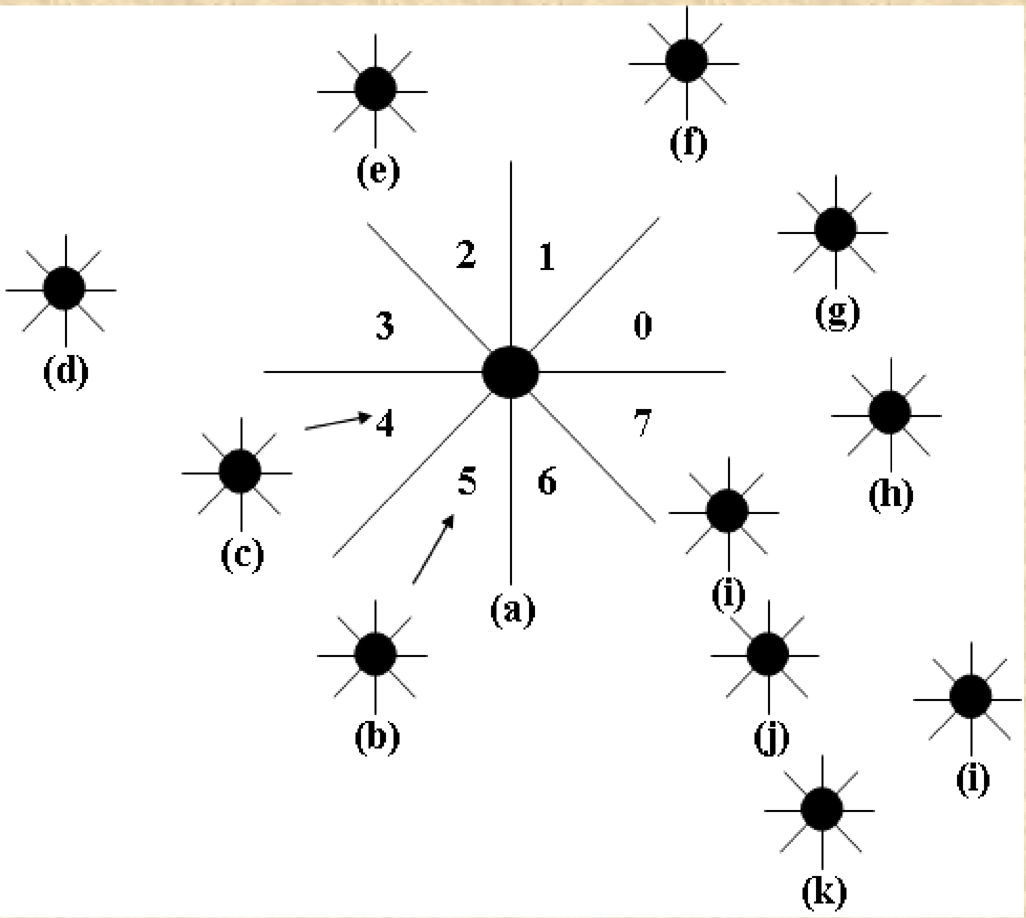
- This type of antenna system allows multiple simultaneous transmission of a packet by a node
- Schemes presented in this subsection do not consider the effect of sweeping delay which is only present in switched beam antenna systems
- *Simple Enhanced Directional Flooding (SEDF)*
  - Whenever a node receives a packet to be forwarded, it starts a delay timer
  - If the same packet is received again before the expiration of this timer, the node makes a note of all the beams where that packet arrived at, and sets them to passive mode
  - Upon expiration of the delay timer, the node will forward the packet in only those beams/directions other than those in which the packet arrived
- *Single Relay Broadcast (SRB)*
  - A node receives a broadcast packet it chooses a subset of its neighbors to forward the packet
  - Only members of this subset are allowed to forward the packet
  - Each node designates one and only one relay node in each direction on the basis of the received signal strength of hello packets
  - Before forwarding, a node waits for a random delay and does not designate any relay node in directions where the packet arrives

# Switched Beam Antenna Adaptive Based Broadcasting Protocols

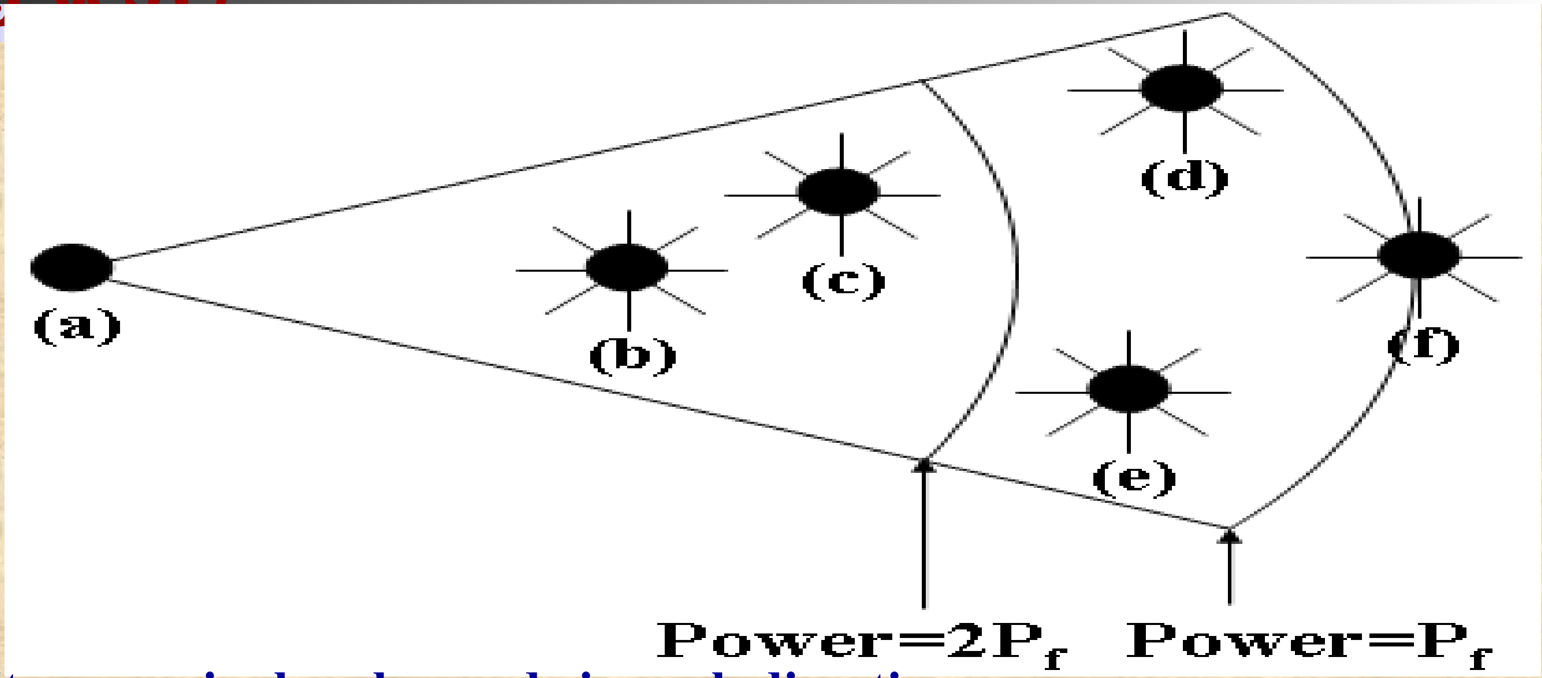
- Broadcasting protocols is harder as the effect of sweeping becomes a major concern
- To mitigate the sweeping delay, a node needs to transmit in fewer necessary beams Protocol Design Considerations
- All the schemes use of some basic design considerations
- One-Hop Neighbor Awareness
  - A periodic exchange of hello packets amongst the nodes is assumed by these schemes
  - A node at any time is aware of which antenna beam its one-hop neighbor lies
  - Usually, this exchange comes at no additional cost as most directional MAC/Routing protocols need one-hop neighbor awareness to operate
  - A node S has to resort to a circular directional transmission of the broadcast packet through all its antenna sectors
  - While S is engaged in this circular sweep, it remains deaf to any incoming packet
  - A sender node S needs to inform its neighbors the additional time they should wait before initiating a transmission towards it
- Novel Optimized Deferring while Sweeping
  - The IEEE 802.11 MAC is followed before transmitting in the first beam of a particular sweep
  - For subsequent beams of the same sweep, only carrier sensing is done before transmission
  - However, if a beam has been marked as busy (i.e., the DNAV is set in this direction), that beam is ignored and the next free beam is picke
- Random Delay Timer: a node starts a random delay timer (RDT) before forwarding a packet so as to avoid any global synchronization

# New Enhanced Directional Flooding (NEDF)

- Whenever the MAC layer receives a broadcast packet, it marks the beams where it will not retransmit
- Using the neighbor table, it marks as passive those beams where there are no neighbors
- Amongst the resulting selected beams, the goal should be to transmit first in regions with maximum uncovered nodes so as to reduce the chances of collisions
- Also, in regions where there is a high probability that nodes have already received the broadcast packet, re-broadcasting should be delayed
- NEDF chooses the beams which are vertically opposite to the beams where the node received the broadcast packet
- Next, the beams which are adjacent to these vertically opposite beams are chosen
- Node (a) receives broadcast packets from nodes (b) and (c) through beams 5 and 4, respectively
- It shall hence rebroadcast only in beams 1, 0, 2, 7, and 3 in that order
- Here we note that beam 6 is ignored as it has no neighbors in that direction
- Finally, beam 1 is chosen over beam 0 as node (b) is farther from node (a) than node (c)



# *Probabilistic Relay Broadcasting (PRB)*




- It uses a single relay node in each direction
- This can lead to a partition in the network
- PRB protocol aims at overcoming the drawbacks found in SRB
- Each node is required to record the received power of the hello packet from the farthest node in each direction
- This is the probability with which it will re-broadcast
- In each sector only nodes which receive the packet at a power less than or equal to 2* $P_f$ will retransmit
- Nodes (b) and (c) do not forward at all while nodes (d), (e) and (f) forward with probability $P_f/P_{fr}$

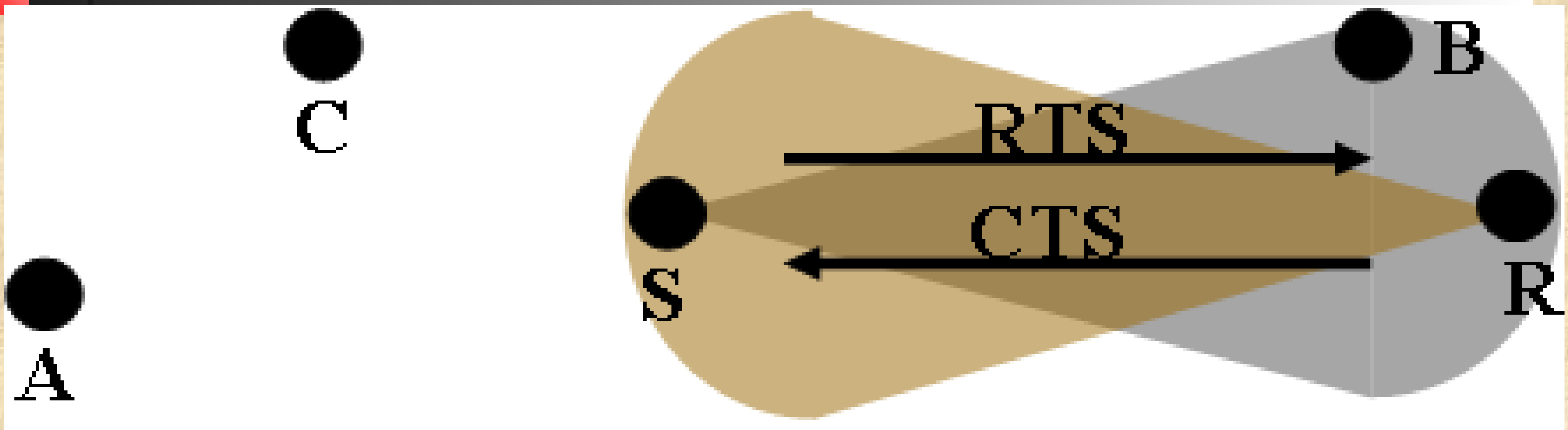
# Medium Access Control

**Existing directional MAC protocols can be divided into single channel and multi-channel**

**Single Channel:**

- ***The Directional MAC (DMAC) Protocol***
  - **Directional MAC (DMAC) protocol has been derived from IEEE 802.11**
  - **DMAC attempts to achieve spatial reuse of the channel and take advantage of the higher transmission range by using DO links**
  - **The DMAC protocol assumes nodes know their neighbors' location**
  - **Similar to IEEE 802.11, channel reservation in DMAC is performed using a RTS/CTS handshake both being transmitted directionally**
  - **An idle node listens to the channel in omni mode, i.e., omni-directionally**
  - **Whenever a node receives a signal from a particular direction, it locks onto that signal directionally and receives it**
  - **Only when a node is beamformed in a specific direction, it can avoid interference in the other remaining directions**
  - **The RTS transmission in DMAC is as follows: before sending a packet, the transmitter node S performs a directional physical carrier sensing towards its intended receiver R**
  - **If the channel is sensed idle, DMAC checks its DNAV table to find out whether it must defer transmitting in the direction of node R**
  - **The DNAV maintains a virtual carrier sense for every DoA in which it has overheard a RTS or CTS packet**
  - **If node S finds it is safe to transmit, then similar to IEEE 802.11 it enters the backoff phase and transmitting the packet in the direction of node R**

# The Directional MAC (DMAC)




## The PRB scheme

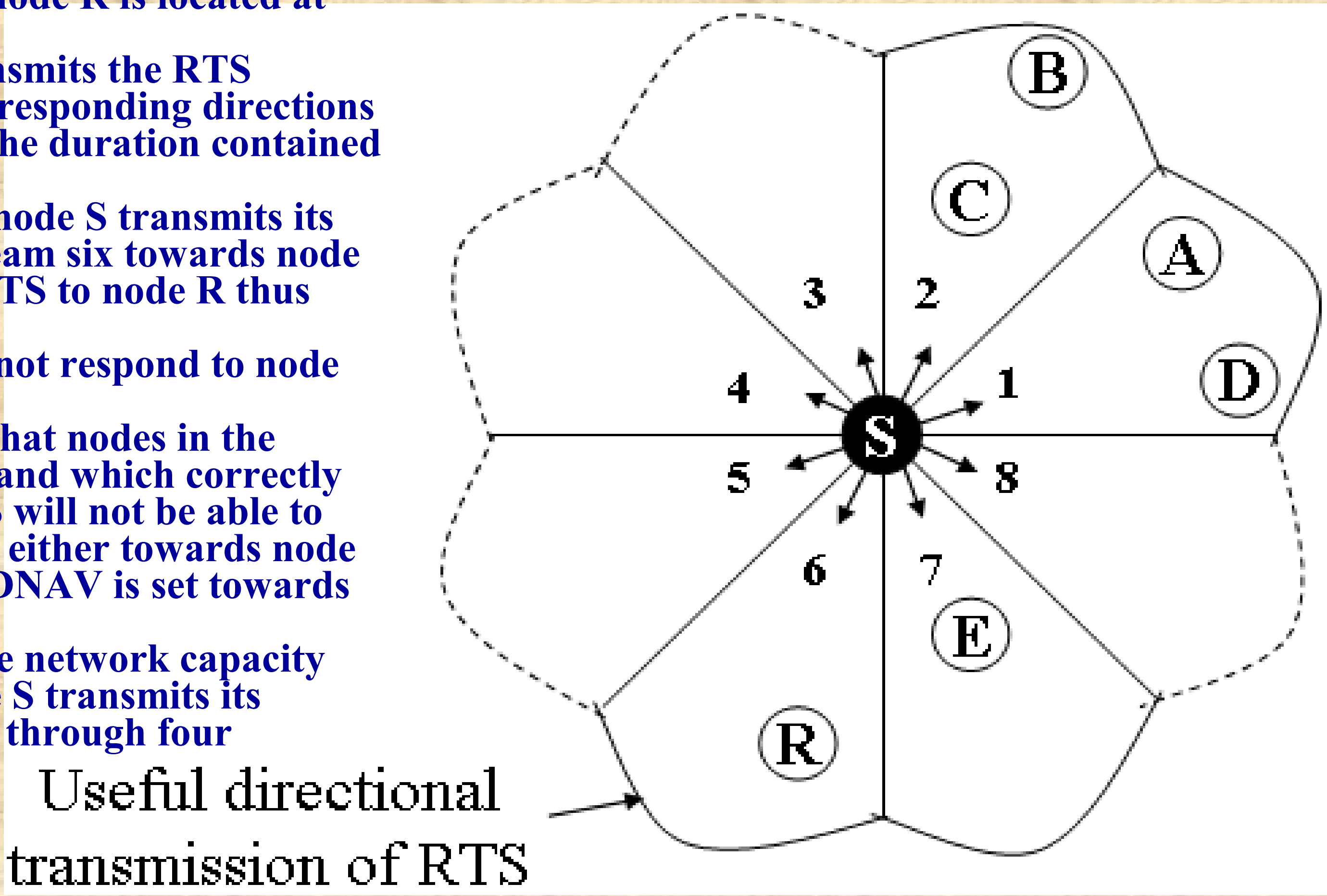
- **PRB is the probability with which it will re-broadcast**
- **The order of re-broadcasting will be similar to the one proposed in NEDF – vertically opposite beams followed by their adjacent beams**
- **Similarly, neighbor-less and busy sectors will be ignored**
- **Nodes which are very close to the broadcast originator have very little probability to rebroadcast**

# The Circular RTS MAC (CRM) Protocol

- Circular RTS MAC (CRM) attempts to overcome some of the limitations found in DMAC
- Contrary to DMAC, CRM does not depend on the availability of neighbors' location information
- CRM employs a circular directional transmission of the RTS packet in a sequential and circular way
- CRM may also decrease the occurrence of node deafness and minimizes hidden terminal problem
- CRM protocol does not completely overcome the limitations of DMAC, and it introduces new shortcomings
- First of all, CRM only prevents node deafness in the neighborhood of the transmitter node while deafness may still occur in the neighborhood of the receiver
- A more serious problem is a sender node S initiates the circular directional transmission of its RTS although it is not at all sure whether its intended receiver node R has correctly received its RTS or not

# The CRM protocol

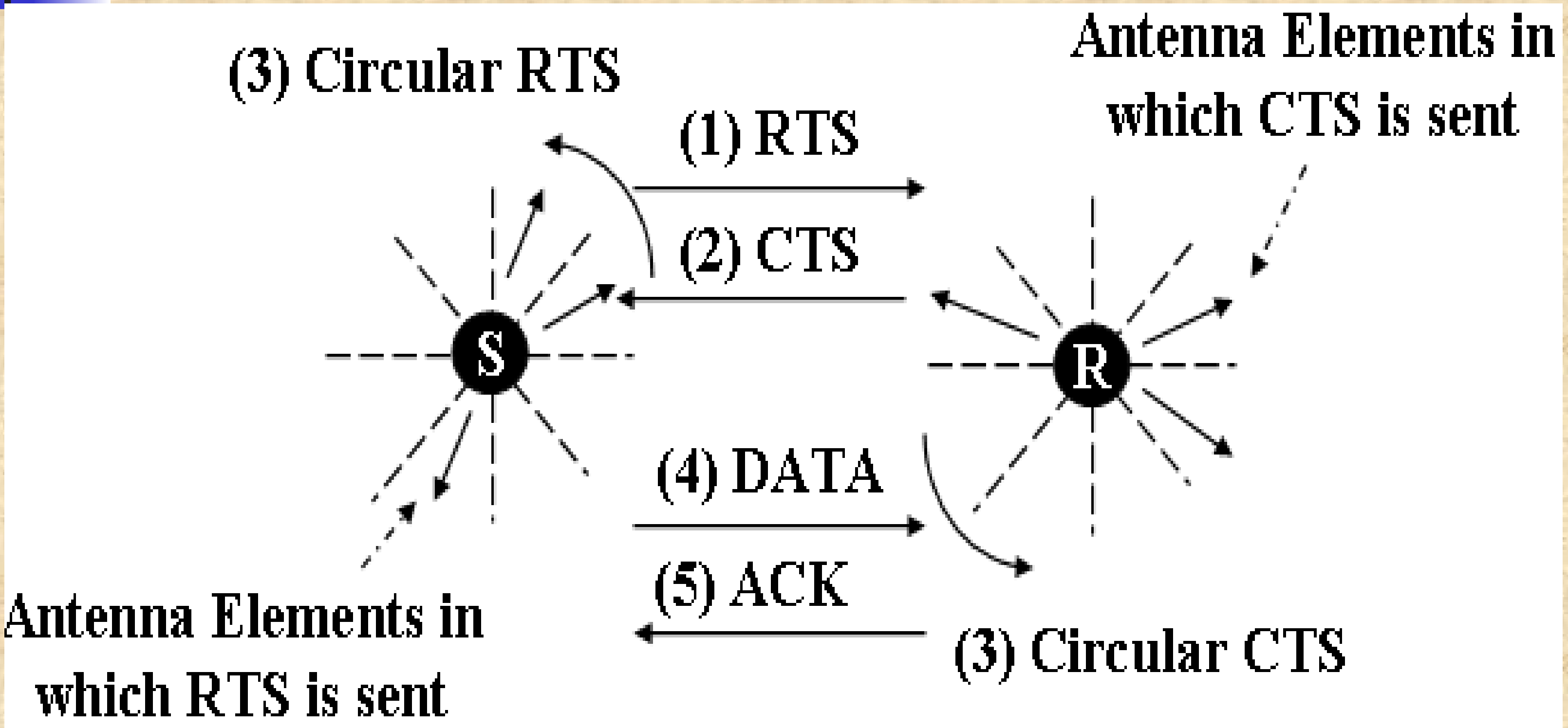
- Each node equipped with eight-beam antenna array
- Sender node S, initiates transmission of a circular RTS through antenna beam one and its intended destination node R is located at the antenna beam six
- As node S circularly transmits the RTS packets, nodes in the corresponding directions update their DNAV for the duration contained in the RTS packet
- Now, assume that when node S transmits its RTS through antenna beam six towards node R, node A also sends a RTS to node R thus causing a collision
- In this case, node R will not respond to node S's RTS
- The side effect of this is that nodes in the neighborhood of node S and which correctly received its circular RTS will not be able to initiate any transmission either towards node S or node R, since their DNAV is set towards both nodes S and R
- Clearly, this degrades the network capacity
- Another limitation: node S transmits its circular directional RTS through four "empty" sectors



# The DAMA and EDAMA Protocols

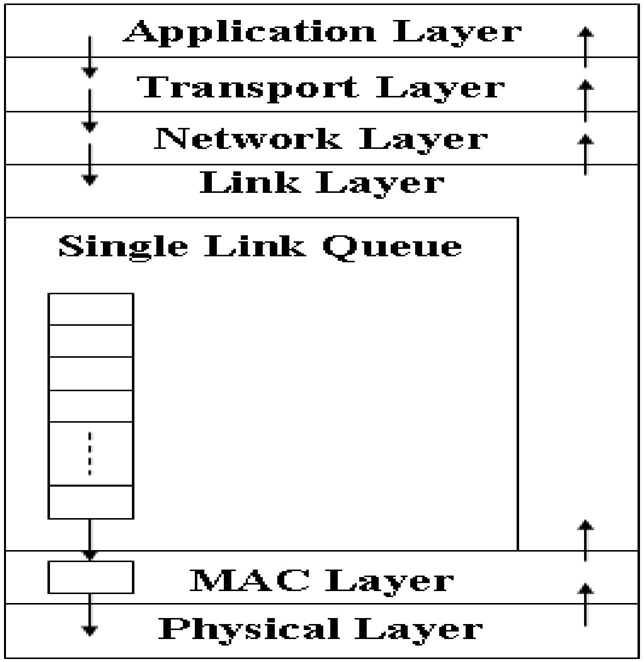
- Antenna Medium Access (DAMA) and Enhanced DAMA (EDAMA) protocols are introduced
- DAMA
  - DAMA employs selective circular directional transmission of RTS and CTS through antennas with neighbors
  - All transmissions in DAMA are directional
  - In addition, DAMA learns its neighbors with time as communication between nodes takes place
  - DAMA employs circular directional transmission of both RTS and CTS
  - DAMA performs similar to CRM by sweeping through all antenna beams and as responses are received, it collects and caches neighboring information

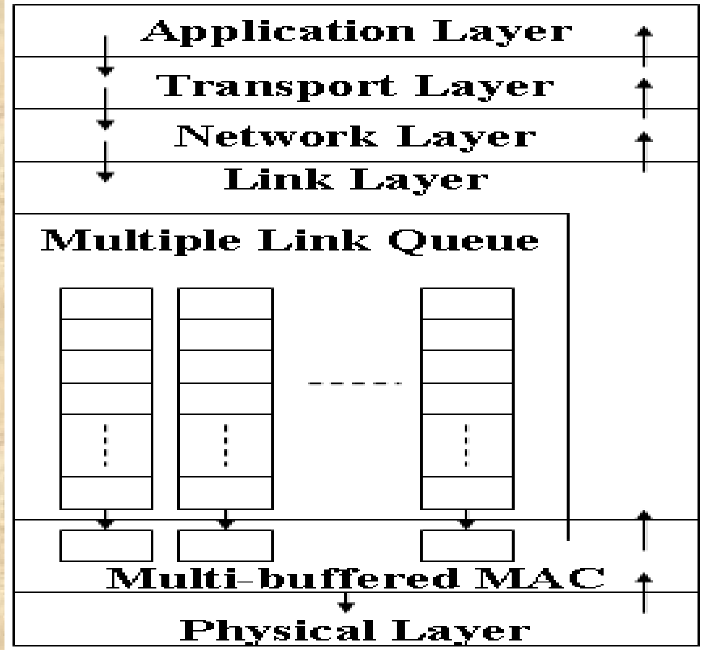
# RTS/CTS/DATA/ACK packet exchange in DAMA




- The first RTS sent is always transmitted in the sector where its intended neighbor is located, and the circular directional RTS and CTS procedure is only initiated once the RTS/CTS handshake is successfully completed
- Both sender and receiver nodes simultaneously initiate the circular directional transmission of their RTS and CTS packets, respectively, to inform their neighboring nodes

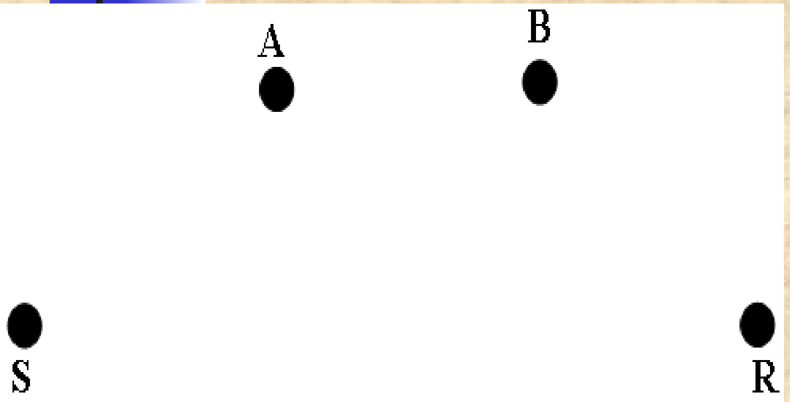
# EDAMA

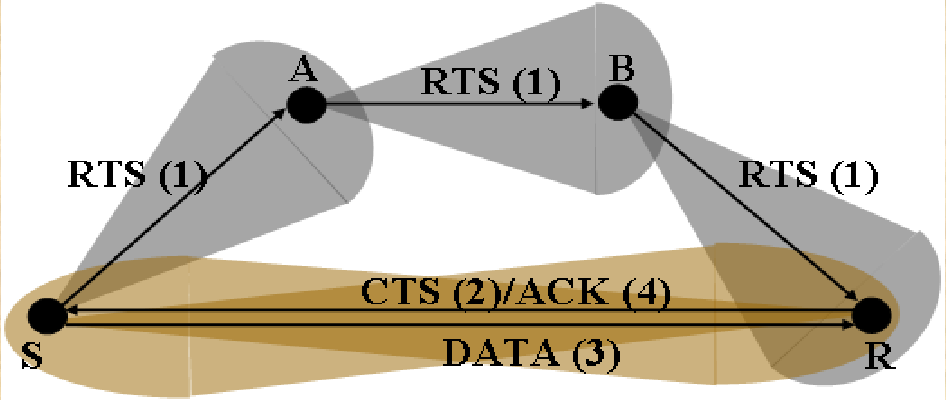



- The link layer has a single queue of packets waiting to be handed over to the MAC layer which is, in turn, a single buffered entity
- Whenever the network layer has a packet to send, it determines the next hop for the packet and places it in the link layer queue
- In case MAC is in idle state, it signals for a packet from the link queue and subsequently buffers it
- It then determines the antenna beam required to transmit the packet and enters into send state
- The MAC will only request another packet from the link layer queue when it has successfully transmitted or given up (e.g., the next hop is unreachable) on the packet it is currently handling
- EDAMA overcomes self induced blocking phenomen by employing a cross-layer design approach wherein the network layer is aware of different antenna beams at the MAC layer
- in EDAMA, routing table has an additional entry called Antenna Beam, which corresponds to antenna beam MAC uses to reach the corresponding next hop

# The Multi-Hop RTS MAC (MMAC) Protocol




- **In idle mode a node listens to the channel omni-directionally with gain $G^0$**
- **Therefore, when a sender node S directionally transmits a packet (with gain $G^d$) to a receiver node R (who listens to the medium omni-directionally and hence with gain $G^0$), a DO link is established**
- **Multi-hop RTS MAC (MMAC) protocol has been proposed built on the basic DMAC**
- **The idea of MMAC is to propagate the RTS packet through multi-hopping until it reaches the intended destination which, in turn, beamforms towards the transmitting node and sends back CTS**
- **Node S has a packet to send to node R**
- **Multi-hop RTS packet transmitted by node S would traverse nodes A and B before it reaches node R**

# The Multi-Hop RTS MAC (MMAC) Protocol

- Upper layer module specifies the MAC layer with necessary beamforming information so as to propagate multi-hop RTS packet through intermediate nodes
- Transceiver profile provided by node S allows all nodes in the route to the intended destination node R to beamform towards each other
- It allows node S to beamform towards node A, node A to beamform towards node B, node B to beamform towards node R and, finally, node R to beamform towards node S
- This way, RTS/CTS/DATA/ACK transmission can be carried out between nodes S and R who are now DD neighbors
- Disadvantages with MMAC:
  - First of all, it relies too much on an upper layer module whose functioning is not clear
  - Secondly, MMAC assumes that all nodes in the route from the source to the destination are available at the time of RTS transmission
  - Thirdly, MMAC brings some routing functionality to the MAC protocol and this by itself incurs significant overhead at the MAC layer
  - Fourth, assume there is a route of length n hops from the source node S to the destination node D
  - Obviously, other issues such as the estimation of the transmission time all the way from source to destination, the management of MAC layer timers, retransmission, and so on, have to properly addressed

# Multi-Channel MAC Protocol

- Multi-channel MAC protocols try to remove some of the MAC layer complexity by employing multiple channels and, for example, using one of the channels to convey important control information
- Obviously, multi-channel protocols also have disadvantages such as higher physical layer complexity, bandwidth allocation requirements and, sometimes, throughput limitations
- *The Simple Tone Sense (STS) Protocol*
  - The Simple Tone Sense (STS) protocol is based on the concept of busy tones introduced by the Busy Tone Multiple Access (BTMA) protocol
  - In BTMA, a station broadcasts a busy tone signal whenever it is receiving a packet
  - This way, all the nodes within the transmission range of the receiving station will sense the signal and remain silent for the duration of the busy tone, thus avoiding collisions
  - Clearly, BTMA employs at least two channels: one for the busy tone and one for data and/or control information
  - STS protocol reuses the idea of busy tones and applies it to directional antennas
  - STS protocol employs algorithms to guarantee that this tone frequency is unique in the neighborhood of any given node
  - STS protocol has some drawbacks:
    - First of all, assigning tones to nodes is a hard task and these tones have to be unique in a node's neighborhood which further complicates the matter
    - Second, the STS protocol assumes that the direction and angles of the beams can be arbitrarily chosen

# The DBTMA/DA Protocol

- Dual Busy Tone Multiple Access for Directional Antennas (DBTMA/DA) is an extension to directional antennas of the DBTMA protocol protocol designed for omni-directional antennas
- The DBTMA is, in turn, based on the BTMA protocol and employs two busy tones instead of one as in BTMA
- DBTMA protocol employs the exchange of RTS/CTS frames to turn on a pair of transmit and receive busy tones, which jointly reserve the data channel
- DBTMA divides a single channel into two sub-channels, namely, a data channel for data frames and a control channel for control frames
- This control channel is further split into two busy tones operating in separate frequencies: the transmit busy tone (BTt) and receive busy tone (BTr)
- By employing the dual busy tones, DBTMA can reserve the channel in both directions
- Whenever a sender node has data to be sent, it first senses the channel for BTr to make sure that the intended receiver is not currently receiving from another hidden node
- The sender then transmits a RTS frame to the intended receiver if BTr is idle
- Upon receipt of the RTS packet, the receiver senses for BTt to ensure that the data it is expected to receive will not collide with any other ongoing neighboring data transmission
- If BTt is idle, it replies with a CTS frame and turns on BTr until the data packet is completely received
- Upon receipt of the CTS packet the sender node will transmit the data packet and turn on BTt for the duration of this data transmission

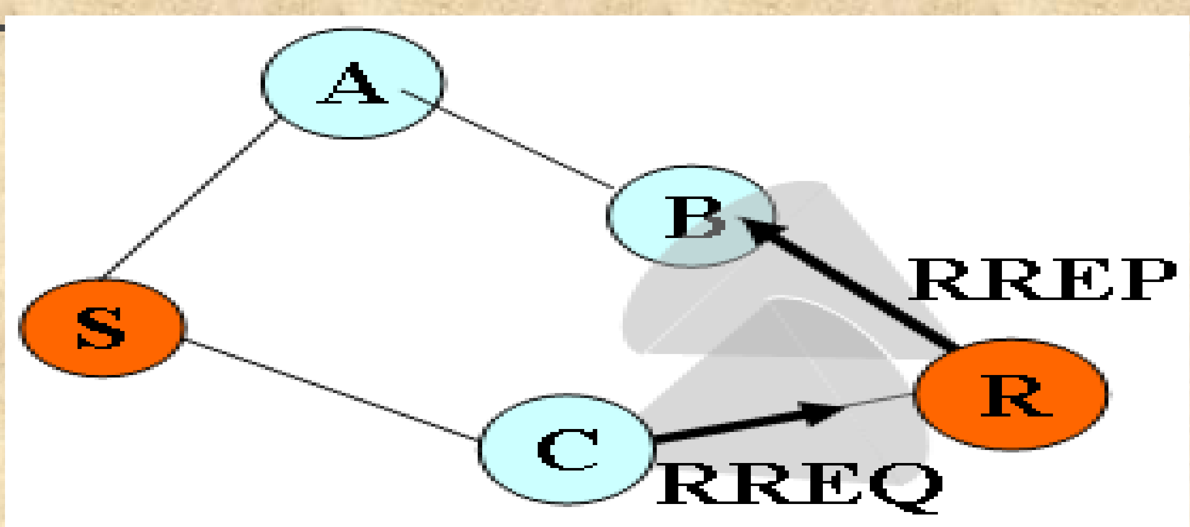
# Other Protocols

- A protocol similar to IEEE 802.11 is introduced but adapted to directional antennas
- It assume the use of several directional antennas simultaneously
- Based on this, the protocol is able to support omni-directional reception which is not possible in all previous schemes
- This is done by employing all directional antennas together, at the same time
- The sender node transmits an omni-directional RTS and the receiver sends back an omni-directional CTS
- Upon reception of the RTS/CTS, the receiver/sender determines the antenna beam these packets were received by using the DoA information
- All neighboring nodes overhearing either the RTS or CTS packet defer their transmissions so as not to cause a collision
- Finally, both the DATA and ACK transmissions are carried out directionally
- One of the benefits is that the interference is reduced by transmitting the DATA and ACK packets directionally
- The use of TDMA with directional antennas is suggested within the context of the Receiver Oriented Multiple Access (ROMA) protocol
- ROMA is a distributed channel access scheduling protocol where each node uses multiple beams, and can participate in multiple transmissions simultaneously
- ROMA follows a different approach than the random access protocols we have discussed so far which employ either on-demand handshakes (e.g., RTS/CTS packet transmission) or signal scanning (e.g., busy tones)
- ROMA is a scheduled access scheme based on a link activation scheme that prearranges or negotiates a set of timetables for individual nodes or links

# Routing Protocol

- The *Scheme 1*
  - The mechanism is applicable to on demand routing protocols running over directional antennas
  - As we know, on demand protocols use flooding of route requests packets in order to discover the intended destination
  - Therefore, the scheme proposes to reduce the number of packets transmitted during route discovery
  - It does so by requiring nodes to record the last known direction to other nodes
  - Therefore, whenever a node S has a route request for node R, it checks if it knows the last direction it used to communicate with R
  - If so, it will forward the route request packet only through the direction towards node S
  - Otherwise, it forwards the route request by sweeping
  - A major drawback: it does not cope up well with mobile scenarios
- *Scheme 2*
  - Contrary to the approach taken by scheme 1 which concentrates on reducing the overhead on the route discovery procedure, this mechanism focuses on reducing the overhead in route maintenance
  - This scheme takes advantage of the increased range provided by directional antennas to bridge possible network partitions
  - As nodes are mobile in ad hoc networks, it might so happen that the network becomes either permanently or intermittently partitioned
  - With the possibility of transmitting over longer distances, directional antennas can help bridge this partitions which would not be otherwise possible with omni-directional antennas
  - This scheme suggests a modified version of the DSR on demand routing protocol which employs directional transmissions only when necessary and for selected packets
  - Whenever a node S has a packet to be sent to node R, it checks its route cache to determine weather it has a route to R
  - If so, it uses this route. Otherwise, it broadcasts a route request packet

# Scheme 3




- This scheme evaluates performance of DSR routing protocol over directional antennas
- In DSR, whenever a source node S wants to find a route to an unknown destination D, it floods the network with route request packets
- As far as the MAC layer is concerned, this route request flooding is mapped to a MAC layer broadcast which is often performed by sweeping
- As sweeping incurs delay, nodes receive route request packets at different times
- If nodes are currently receiving a route request packet form one direction (hence deaf to all other directions) they may miss route request packets coming from other directions
- S floods a route request for node R
- Here, we see that node R receives the first RREQ through node B and, as per DSR, send back a RREP right away
- While it sends the RREP to node B, node R misses the RREQ coming from node C which is shorter in terms of number of hops
- The route reply is sent over a sub-optimal route
- Due to this problem, this scheme proposes a delayed route reply mechanism so that the destination node after  receiving a route request, waits for a certain amount of time before responding with a route reply
- The idea is, other route requests may come through better routes

# Conclusions and Future Directions

- With current technological advancements, there is no doubt that directional antennas will become an integral part of future MANETs as means to considerably enhance its capacity
- However, a directional antenna creates many difficulties with regard to protocol design as it impacts almost all layers of the protocol stack
- There are many other issues still open and need further investigation
  - First of all, the antenna models being used for the design of upper layer protocols (e.g., MAC and routing) are too ideal
  - Secondly, power control is also an important aspect, as it may also create problems in a heterogeneous environment
  - Thirdly, it is necessary to analyze in detail the effect of using directional antennas on the transport layer
- Another challenge is to analyze the capacity improvement of directional antenna systems
  - It would be very interesting to know the capacity limitations with directional antennas
  - Finally, further investigations are needed to explore the issue of multi-packet transmission and reception